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THE APPLICATION OF EXPANDABLE HONEYCOMB TO THE FABRICATION OF SPACE STRUCTURES

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I. INTRODUCTION

The exploration of space will undoubtedly require a wide variety of large structures. Several approaches to producing those large structures become immediately apparent. Small modules or components of the overall structure could be transported into the desired position and assembled into the overall structure. Another approach is to develop an expandable structure which has a small packaging volume and can be transported into the desired position in its fully assembled configuration. Of equal importance to the small packaging volume is the strength-to-weight ratio of the finished structure. Excess weight transported into the space environment means larger rockets and highly increased costs of launch.

GCA Viron Division, in conjunction with several subcontractors, have developed a concept which produces a structure with a low packaging volume and provides high strength with a low weight penalty. This paper will discuss the development phases, materials research, fabrication techniques, experimental development, and actual model space structures which have been fabricated based on the expandable honeycomb concept.

II. STRUCTURAL CONCEPT

Several years ago Mr. F. Forbes and Mr. S. Allinikov of the Air Force Research and Technology Division were investigating methods to produce expandable structures. One of the concepts they originated was to utilize a woven fabric honeycomb material which could be fabricated into structures of essentially any configuration. That structure could then be impregnated with a liquid plastic resin system and still be in a packageable form. Upon deployment into the desired environment, the plastic resin system could be rigidized by vapor phase catalysis,

plasticizer boil-off, or some other technique. There would remain a semi-permanent structure with high strength-to-weight ratio and a number of other advantages. This concept produces results which are comparable to the well known, excellent rigid conventional honeycomb properties.

III. EXPANDABLE STRUCTURES GOALS

The goals listed in the following section are in general oriented toward outer space application. However, this concept is equally applicable to a terrestrial environment and the goals listed are usually also desirable for that application. A high strength-to-weight ratio is desirable since every pound which must be carried into a remote environment normally adds to the overall cost of the completed item. Similarly a high expansion ratio is desirable to provide as small a package as possible. This is especially important in the case of rocket transportation of large structures into the space environment. In that case a restriction of overall dimensions of the packaged item is usually present. It is desirable to require no energy, or very low energy, to expand and rigidize the final structure. The amount of energy required usually directly affects the overall weight and the packaged volume of the structure.

Simplicity of design is a very important factor in structural engineering. This is especially true with expandable structures which are intended for deployment and rigidization in a remote area. The design engineer wants very few required steps between the packaged condition and the final usable condition to feel assured that a high ratio of success can be guaranteed. He also desires to conduct as many proving tests as is possible before the expandable structure is packaged. It is even desirable to have a system where the actual item intended for space use can be inflated, rigidized, inspected, reflexibilized, and packaged for transportation into the space environment.

Any concept chosen for development must be one which can be shown to be applicable for space use through laboratory experimental efforts. The shelf life of a system in its packaged configuration is very important. The structure may be prepared for transportation into the remote area quite some time in advance of the actual use. Similarly, it may be desirable to prefabricate a number of structures for use at a later time. It is known that meteoroids are present in the space environment and the concept should be resistant to that hazard.

The fabrication of accurate structures requires that the structural material have dimensional stability in its final rigidized form. Plastic resin systems are known to shrink during cure but it is desirable to keep that amount of shrinkage to a minimum.

IV. MATERIALS RESEARCH

A. General

Structures fabricated from expandable honeycomb have two major material components. The fabric honeycomb substrate material acts as a carrying agent for the second component, the rigidizing plastic resin. Each component has a discreet function to perform. The fabric, in addition to acting as a substrate material, is the medium for fabricating the structure into the desired shape. The fabric also greatly enhances the physical properties of the rigidizing resin system. The resin system itself serves to tie the individual fibers in the base fabric together and cause them all to act as one unit. It accomplishes this task by encapsulating the individual fibers and acting as a shear surface between each of the individual fibers such that if elongation occurs in one fiber the load is transferred to adjacent fibers.

B. Structural Material

The original intent was to use an actual honeycomb fabric, with hexagonal or square cells, for the fabrication of expandable structures. This configuration would provide a material with no large spans of unsupported fabric in the face material. It should, therefore, be possible to approach the ultimate tensile or compressive strength in the fabric faces before buckling would occur. Also, there would be bi-axial strength since there would be no longer span in one direction than in the other direction. Early investigations showed that there is no actual fabric honeycomb material available as an integrally woven fabric, however, there are several sandwich type fabric materials available.

One such fabric, produced by Raymond Development Industries, incorporates a web type configuration integrally woven between two faces of material. Those webs can only be woven in one direction of the fabric. The finished sandwich, therefore, has considerably more strength in one direction than it has in the other direction. Materials of this nature which have been investigated were not designed especially for inflatable, expandable structures. The loose weave which was used did not provide a material with low enough porosity to make them completely satisfactory for this application. Figure 1 shows an example of this web type material.

Another type of sandwich type fabric material is an outgrowth of the velvet industry. This material, obtained from A. Wimpfheimer and Bro., Inc., Stonington, Connecticut, might be referred to as a drop thread material since it consists of "dropped threads" which are integrally woven into two separate fabrics being simultaneously woven a fixed distance appart. Two pieces of velvet fabric can be produced from this material by cutting the drop threads between the two faces of material. Without cutting those drop threads, a sandwich material is produced which presents a high moment of inertia simply because the faces are far from the neutral axis. The column action of each of the drop threads tends to hold the faces in a fixed position. Variations to this drop thread material can be made by dropping the threads in rows in one direction. Figure 2 shows an example of that fabric. This again provides a unidirectional material. It is also possible to place drop threads in perpendicular rows such that a "quasi-honeycomb" material could be produced. If the drop threads are dense enough, it is conceivable that a tying together action of a plastic resin system might provide a rigid shear resistant wall. These drop threads could also be uniformly scattered at nearly any desired density throughout the material. In that manner, the distance between each of these columns could be varied as desired.

We have produced, in limited quantities, a tailor-made fabric which in cross section looks as is shown in Figure 3. That material can be sewn or bonded from flat woven sheets of fabric. The core is also produced from just a flat piece of material which can be sewn between the two faces as shown. The very great flexibility of design which is available here allows a material to be made up especially for each particular application. One very important point in using sandwich type fabric material in an inflatable expandable structure is that it is necessary to have porosity control in the material so the structure can be inflated into the desired shape. This material lends itself very well to that porosity control in that the faces can be made up from very tight woven fabric or could even have plastic material incorporated directly into the faces. The material can also be tailor-made to meet the strength requirements. In the sketch T_1, T_2, and T_3 can all be different or they could even vary throughout a running length of the fabric material. Variable web spacing is possible. One dimensional

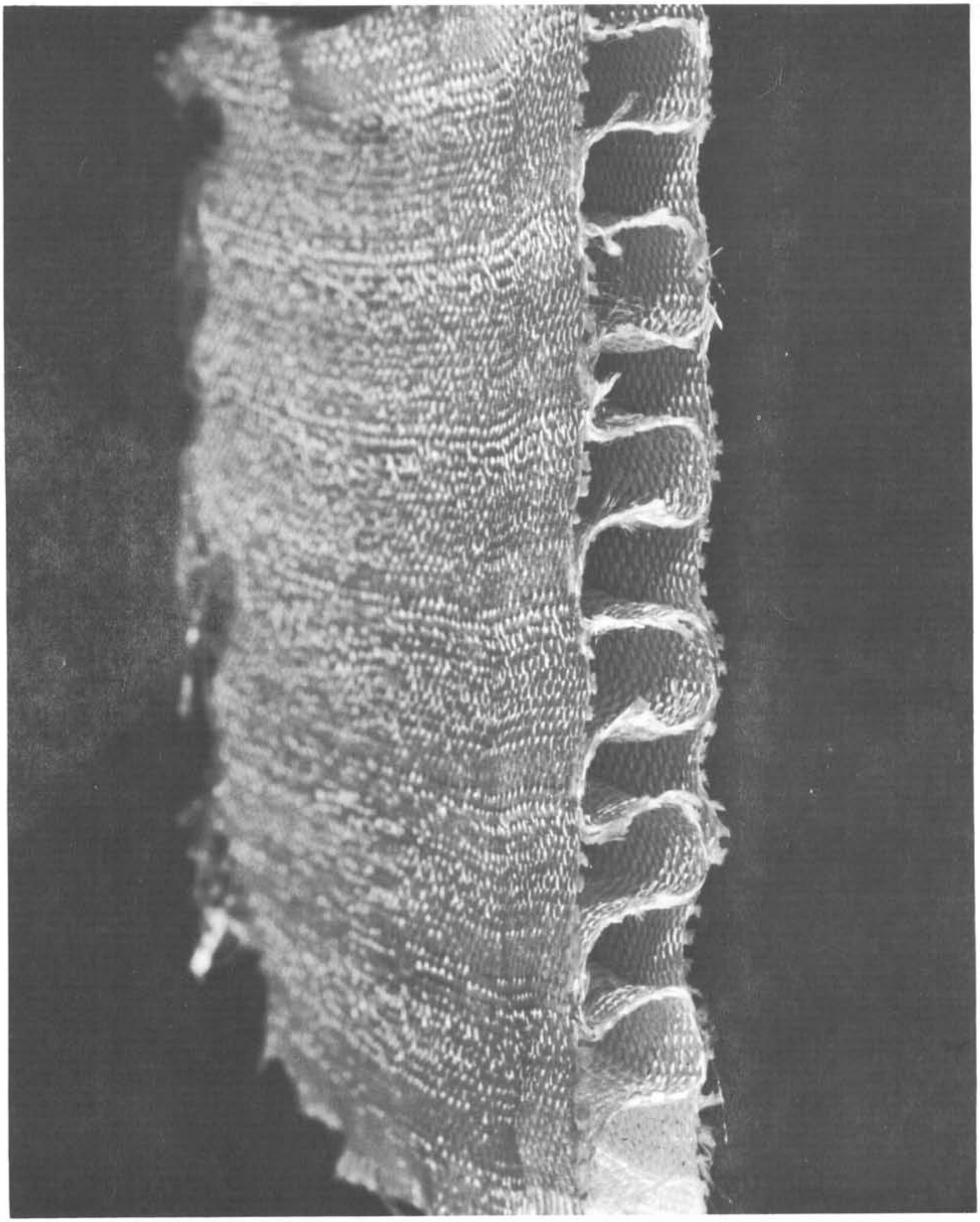

FIGURE 1 - RAYPAN FLUTED FIBERGLASS MATERIAL

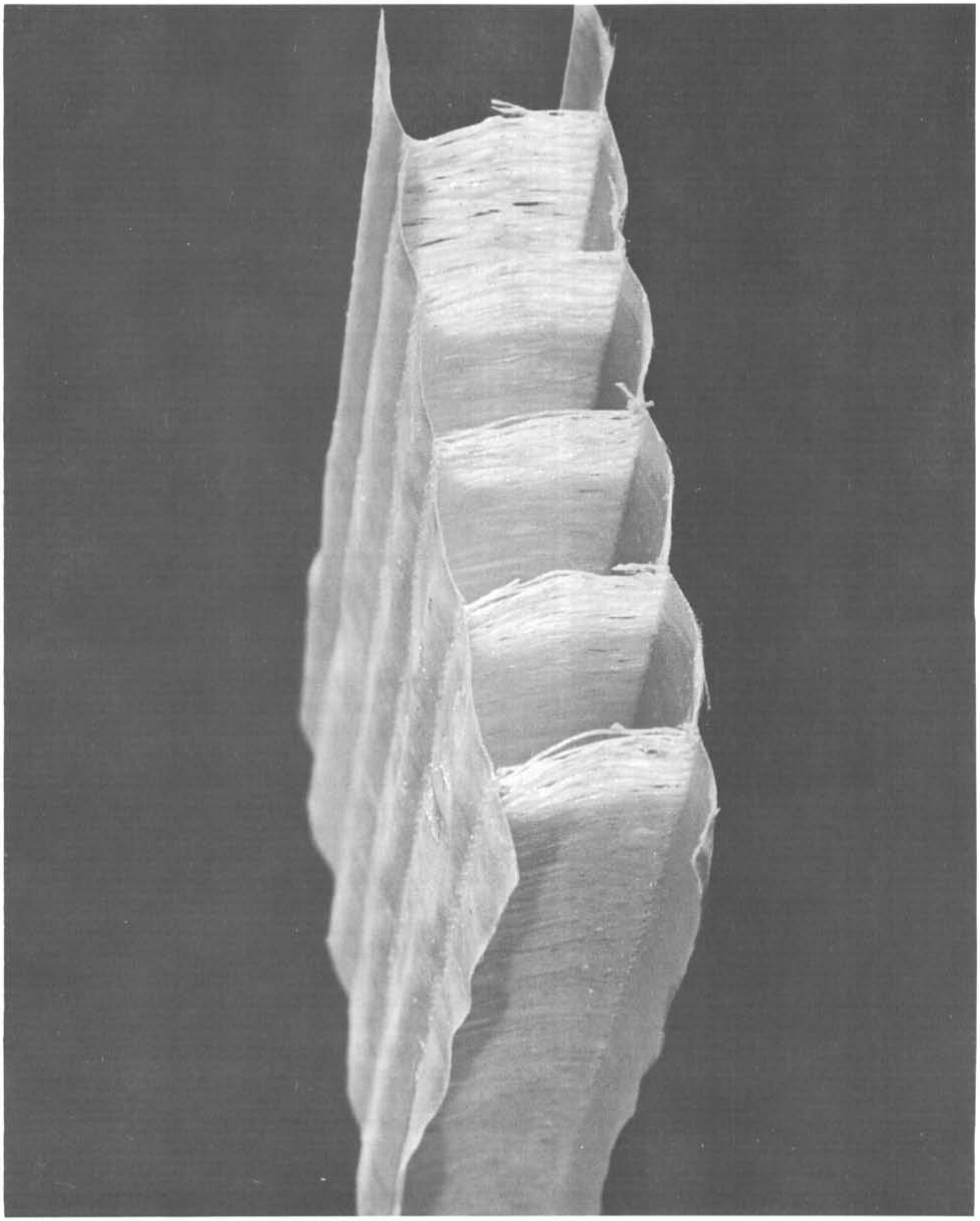

FIGURE 2 - DROP THREAD NYLON MATERIAL

curvature can also be incorporated by making W_1 different from W_2 or W_1 and W_2 could even vary along the fabric. The core configuration could also be one of vertical webs.

Another important aspect in selecting the proper fabric for the fabrication of expandable structures is to make a proper selection of the basic material which goes into the fabric. Probably one of the most important considerations is to obtain as high as possible of a strength-to-weight ratio. Of the materials which can be woven into a fabric, it is known that fiberglass has the highest strength-to-weight ratio. This is closely followed by such materials as Fortisan and some of the other synthetic fibers. Also of high importance is the fact that whatever material is chosen must be able to withstand the environment in which it will be used. Again fiberglass and some of the synthetics withstand the terrestrial or space environment, especially if they are coated with a plastic resin system.

To produce an expandable structure from these fabric materials the problems which will be associated with the actual fabrication must be considered. As a general rule it is easier to fabricate to an exact shape using the lighter weight materials. Resin compatibility for nearly any of the fabrics can be accomplished through proper surface treatments. These surface treatments are mainly used to make a better bond between the surface of the individual fibers and the resin itself. Availability of the material must be considered in the selection of the materials. Some newly developed synthetic fibers or some of the more unique glass fibers are not always available even though they may be desirable for a particular application. Cost of the basic material is also an important factor. Some of the very complicated procedures which must be followed in producing fibers make them very expensive.

C. Plastic Resin System

The plastic resin system which is used in combination with these sandwich type structural materials serves, as one main function, to rigidize the fabric material. As the plastic resin system which encapsulates the individual fibers in the fabric rigidizes, it imparts rigidization to the composite. The resin system acts to tie each of the individual fibers in the overall fabric together such that they will act as one unit. If one of the individual fibers elongates under tension the resin system transfers part of the load to the adjoining fibers. By this mechanism, a uniform distribution of load throughout the load bearing area can be accomplished. The resin system can also be designed to act as a porosity reducer in the fabric material by filling the open spaces between the individual strands in the weave. In order to achieve a satisfactory distribution of load throughout the structural material, it is necessary to have complete and uniform impregnation of the fabric material. This can best be accomplished if the resin system is in a liquid form with a workable viscosity. In addition, it is desirable that the resin system should be easily handled, non-toxic, not affected by laboratory environments, and should require no special storage conditions.

Resin systems which are available to rigidize fabric structures can mainly be classed in three groups. A vapor cured resin system consists of a completely uncatalyzed, long chain molecular system which can be cross-linked with a catalyst provided in a vapor phase. The cross-linking frequency or netting index determines the degree of rigidity. This is a non-propagating system, i.e., every molecule which is to be cross-linked such that it contributes to the three dimensional rigidity must be contacted

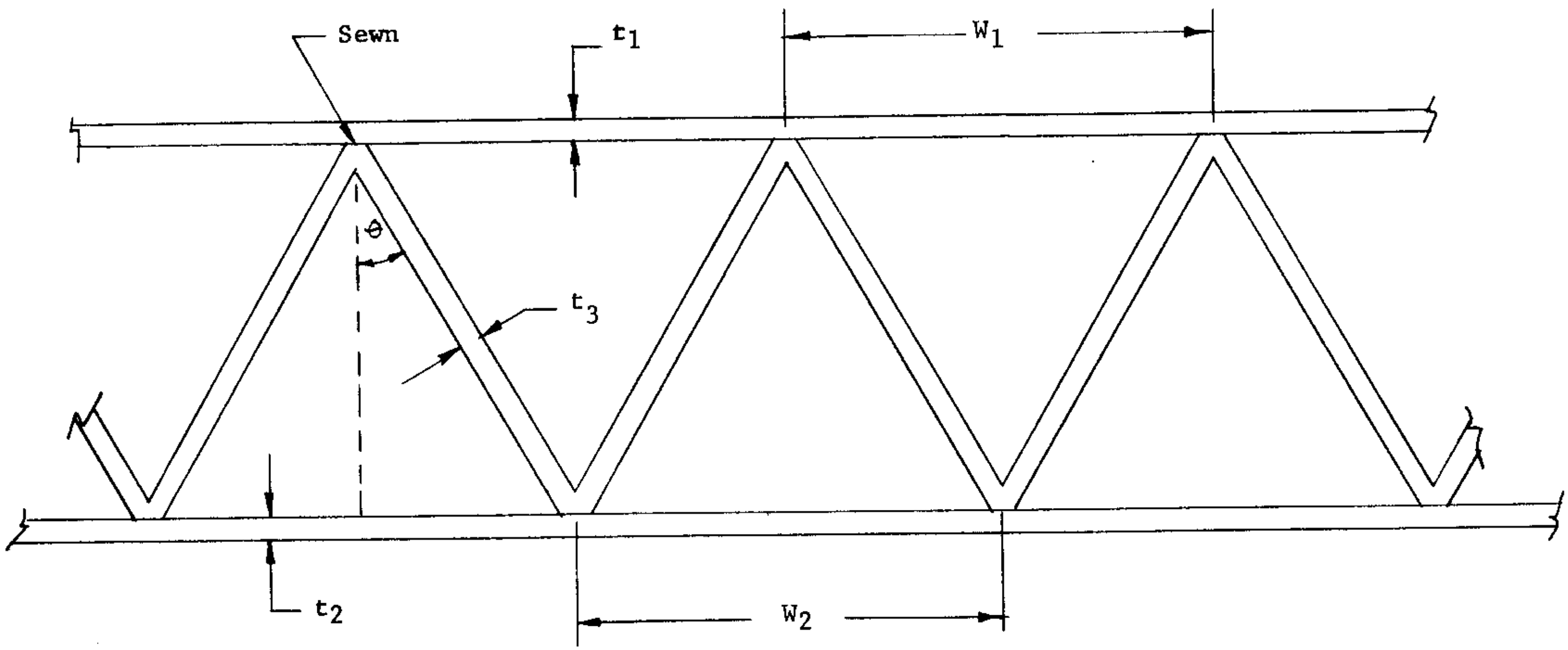

FIGURE 3. TAILOR-MADE SANDWICH MATERIAL

by the vapor catalyst. That catalyst might be supplied from a compressed gas supply or a liquid at pressures below its vapor pressure. Those vapors then can be manifolded such that they are forced through the resin impregnated structural material. The same catalyst vapors can be used as the inflation gas. This type of curing mechanism lends itself very well to an "on command" cure. Examples of this type of resin system are polyurethanes which can be cross-linked with water vapors, polyesters which can be cross-linked with amine vapors, and epoxies which can also be cross-linked with amine vapors.

The plasticizer boil-off system depends only on the evaporation of solvents which have made large molecular structures into a liquid form. This type of system gets its strength from cohesive action or molecular attraction. The resin system, with properly chosen solvents, could have an infinite shelf life. This system itself is extremely simple in that if a resin impregnated structure is placed in a vacuum environment, and the plasticizer has been chosen such that its vapor pressure is sufficiently high, it will automatically cure. The process of cure appears to be a combination of the evaporation of solvents and the migration of those solvents through multiple molecular layers of encapsulating resin. Examples of this type of resin system are gelatin and acrylic. The gelatin system lends itself very well to B-staging into a rubbery and non-tacky packageable item.

An intimately mixed resin system consists of a long chain molecule with the catalyst mixed directly into the liquid resin system. This type resin system has a limited shelf life which possibly could be overcome by storing at low temperature where organic reactions would not take place. Very high strength could be obtained with this type of resin system since the catalyst is previously mixed directly into the resin system and every molecule could theoretically be cross-linked. It appears that this type of resin system could present many very serious problems before it could be shown to be usable for an actual space application. There are also other resin systems such as ultra-violet or high energy radiation cross-linked or heat activated resin systems. These resin systems could provide very good strengths, but they could also provide very serious problems unless adequate shielding from radiation or heat was provided.

D. Resin Substrate Combination

The real item of interest in the fabrication of expandable structures using this concept is how the combination of the substrate and the resin system will perform. The characteristics of the combination can be predicted if the characteristics of the substrate and the characteristics of the resin are known. Such things as the tensile strength of the fiber, the compressive strength of the resin, and the modulus of elasticity of each, which are easy to determine on the materials alone, can be used to estimate the resultant strengths. In general it can be said that tensile loads in a fiber-resin combination are taken by the fibers and that the compressive loads are taken by the resin. These ideas can be taken into account in the design of a sandwich to most efficiently provide either the amount of tensile material or the amount of resin for compression that is required in different parts of the specimen. If the design criteria of a particular structure is one of tension only, such as in a pressure containing vessel, the sandwich type material is not as efficient as filament winding for instance. However, as soon as the design criteria is one of bending, it has been determined that sandwich type material weighs only approximately 1/5 as much as a filament wound structure.

An example of the properties obtainable with various materials are as shown below in psi:

Material	Tensile Strength	Flex Strength	Modulus of Elasticity
181 Fiberglass Cloth	40,000		6×10^{6}*
Urethane Film	10,000		3×10^{6}
Gelatin Film	13,000		1×10^{6}
Urethane - Glass	60,000	30,000	8×10^{6}*
Gelatin - Glass	60,000	40,000	10×10^{6}*

* Based on area of glass fibers only.

V. EXPERIMENTAL DEVELOPMENT

A. General

This expandable honeycomb concept has been experimentally developed for a number of different configurations. They can generally be classed as shelters or solar collectors. These two items present completely different problems in fabrication and design. The solar collectors are a problem in creating a light weight structure with a high degree of accuracy and the shelters study is more of a problem in obtaining a high strength-to-weight ratio structure in a compact package. These two completely different problems demonstrate the flexibility of design that is available with this concept.

B. Solar Collectors

1. Concept

The solar collector concept, as it has been developed to date, utilizes a sandwich type fabric structural material in combination with a rigidizable plastic resin system to maintain a plastic reflective surface in the shape desired. The structural material is bonded to the reflective plastic surface. That bonding layer also helps to eliminate fabric show-through and orange peel effects. After the composite is formed into the paraboloidal shape it could then be attached to a pressure containing spherical balloon which would be inflated to "shape" the collector. The whole system would be packaged in a canister for transportation into space. After being placed into the desired position, the canister would be opened and the assembly deployed. Inflation into the proper shape would be effected by releasing predetermined quantities of subliming materials in the balloon.

If the rigidizing resin used were a plasticizer boil-off type, that would be the final step in the deployment and rigidization of the structure. If a vapor cured resin system were chosen, the catalyst container and a manifolding system to direct the vapor to the resin impregnated structural material would be required. After deployment and rigidization of the solar energy concentrator, the pressure container would be removed by means of a hot wire or pyrofuze technique. The subliming materials contained on the plastic material would provide thrusting action to push the thin material away from the solar energy concentrator.

The total assembly consists of the solar collector composite itself, a plastic pressure retaining balloon, the inflation gases required, and a canister. Based on present state-of-the-art, the total assembly weight is estimated to be approximately 1/2 lb per sq ft of projected area in addition to the weight of the required canister.

2. Small Models

Early experimental efforts were devoted to assembly of the complete composite as eight inch model collectors. This series of models was used to develop assembly techniques, investigate resin impregnation approaches, screening for applicable materials, and learning the most appropriate cure approaches. Variables such as different plastic reflective surfaces, different flexible adhesive layers, different sandwich type structural materials, different rigidizing resins, and different cure conditions were investigated in this series.

3. Two and One-Half Foot Diameter Models

This experimental size was the main tool in further developing fabrication, assembly, impregnation, and curing techniques which were used. Again, various plastic reflective surfaces, adhesive layers, structural materials, and rigidizing resins were experimentally tested. It appears that either the vapor cured urethane or the solvent release gelatin system offers the most promise and can be applied to this type structure interchangeably with only minor variations in the construction. Figure 4 shows a rigidized 2½ ft diameter solar collector model.

4. Five Foot Diameter Models

Several five foot diameter solar collector models were assembled, using the concept outlined above, and were vacuum cured using a polyurethane vapor cured resin system. The structures were sufficiently flexible for packaging, cured in about two hours, and had sufficient rigidity to retain their shape. Figure 5 shows a cured five foot diameter solar collector model.

5. Ten Foot Diameter Solar Collector Models

A ten foot diameter solar collector was assembled from one mil, aluminized Mylar, a flexible epoxy adhesive layer, and approximately one inch deep nylon drop thread material. The structural material was impregnated with a polyurethane resin system and cured in a stratospheric vacuum chamber at WPAFB. The internal pressure which retained the paraboloidal shape was not maintained throughout the seven hour cure cycle and major distortions resulted in the reflective surface. The structural material had sufficient rigidity to retain the overall shape after cure. Figure 6 shows the reflective surface of that 10 ft diameter collector.

C. Shelters

1. Concept

Heavier, more rigid structures which have been studied have included various cylinders, space type man shelters, and terrestrial quonset type structures. In general, the procedure is to arrive at a best design and fabricate the structure into the desired shape using dry sandwich type structural material. After complete assembly the structure can be impregnated with the liquid resin system and still be completely flexible for packaging. This structure is then ready for deployment, inflation, and cure of the plastic resin system.

An inflatable structure always tends toward a spherical shape, therefore, it appears that flat surfaces should be avoided if possible. Restraining lines could be used to force the inflated structure into semi-flat shapes. The actual inflation of these structures into their desired shapes can be accomplished in several ways. In a vacuum environment, the catalyst vapor pressure or the pressure which is developed by the plasticizer is usually sufficient to inflate the structures into the desired shape. The porosity of the structural material must be kept sufficiently low so that a pressure differential can be maintained across the face of the structural material. An impermeable bladder could be used to force inflation of the overall structure. The high strength advantages that are inherent in a sandwich type material can only be obtained if the sandwich itself is fully expanded. This sandwich expansion can be incorporated directly into the design and fabrication. For instance, a cylinder with a known radius of curvature can be fabricated with the outer face of the sandwich material longer than the inner face by the differences in the circumferences.

2. Small Models

Early experimental development of fabrication, impregnation, deployment, cure, and testing techniques which were applicable to the production of shelter type structures were conducted on small sandwich material cubes. The cube was very simple to fabricate and provided a quick and cheap experimental program. Various sandwich materials, resin systems, and cure conditions were investigated. A number of eight inch shelter models were also fabricated and rigidized using different materials and resin systems. These models provided a basis for investigation with larger sizes. Figure 7 shows a vacuum cured eight inch model shelter which was cured with a vapor cured polyurethane.

3. Cylinders and Shelters

A number of cylinders and shelters approximately 3½ ft in diameter and 4 ft long were the next experimental development step. Different sandwich type materials and resin systems were used during the phase. This series covered a pressure range from atmospheric down to approximately 10^{-6}mm Hg and used both a vapor cured urethane and a gelatin resin system. Figure 8 shows a 3 ft diameter cylinder which was vacuum cured with a gelatin resin system in approximately 6 hours. The flat section was not intentional, it resulted from the weight of the structure during cure. Figure 9 shows a 7 ft diameter by 8 ft high

space shelter that was cured in a vacuum environment with a vapor cured urethane resin system. That cure required approximately seven hours. Inflation was with residual gases and catalyst vapors.

4. Aerospace Maintenance Dock

A 13 by 15 ft quonset type structure (semi-cylinder) was fabricated from expandable honeycomb material. The especially designed sandwich material included in that structure was fiberglass. That structure was completely assembled as dry fabric sandwich material, impregnated with a polyurethane resin, inflated with an axial flow blower, and cured with the water vapor present in the atmospheric air. The 400 lb structure was designed to withstand 100 mph winds and a 30 lb per sq ft snow load with a safety factor of $1\frac{1}{2}$. A 2 inch deep sandwich was chosen for the roof section with flutes running in the circumferential direction. The structure initially packaged in approximately 3 cubic feet for an expansion ratio of about 330 to 1. Figure 11 shows the deployed and rigidized structure.

5. Cylindrical Space Structure

A current study is developing a 10 by 25 ft cylinder from expandable honeycomb. It will incorporate an internal bladder for pressure retention, an integrally connected floor, it will be packaged between canister-half bulkheads, it will be remotely deployed in a 10^{-6}mm Hg evnironment, and will contain a buffering layer to protect the internal bladder both from meteoroids and from internal damage.

The fiberglass-plastic bulkheads were prepared by the WPAFB Experimental Fabrication Division by multiple layup of fiberglass and epoxy resin over a mold. They were then sanded and machined to provide the smooth surfaces necessary to form the "10 ft diameter vacuum chamber".

Several 1/6 size models have been fabricated and rigidized. Complete impregnation of the structural material and rigidization within $1\frac{1}{4}$ hours have been accomplished. This program is utilizing a vapor cured urethane system.

Figure 12 shows an artists concept of the packaged, deployed, and rigidized configuration, Figure 13 shows a 1/6 size model packaged within the canister-half bulkheads, Figure 14 shows the deployed 1/6 size model during cure, and Figure 15 shows the structural material with the bulkheads removed.

VI. CONCLUSIONS

A. The expandable honeycomb concept has been shown to be a feasible and desirable approach to providing expandable structures for space and remote area use. Large load carrying structures and solar collectors which require a great degree of accuracy are all within the fabrication and rigidization realm of possibility.

B. A number of plastic resin systems have been developed which are satisfactory for space application. The most promising appear to be a vapor cured urethane system and a gelatin plasticizer boil-off system.

FIGURE 4 - VACUUM CURED 2 FT SOLAR COLLECTOR MODEL

FIGURE 5 - VACUUM CURED 5 FT DIAMETER SOLAR COLLECTOR MODEL

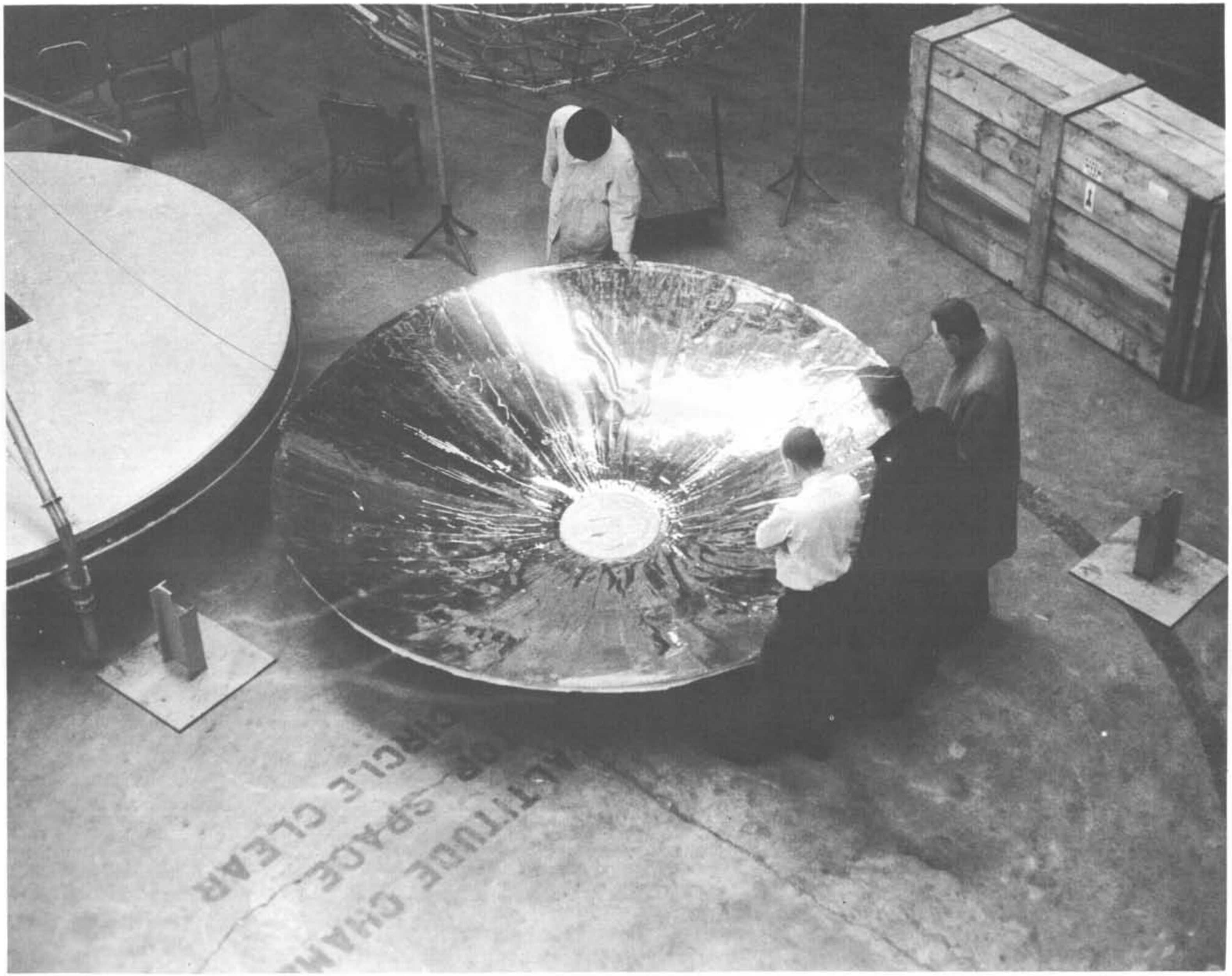

FIGURE 6 - VACUUM CURED 10 FT DIAMETER SOLAR COLLECTOR MODEL

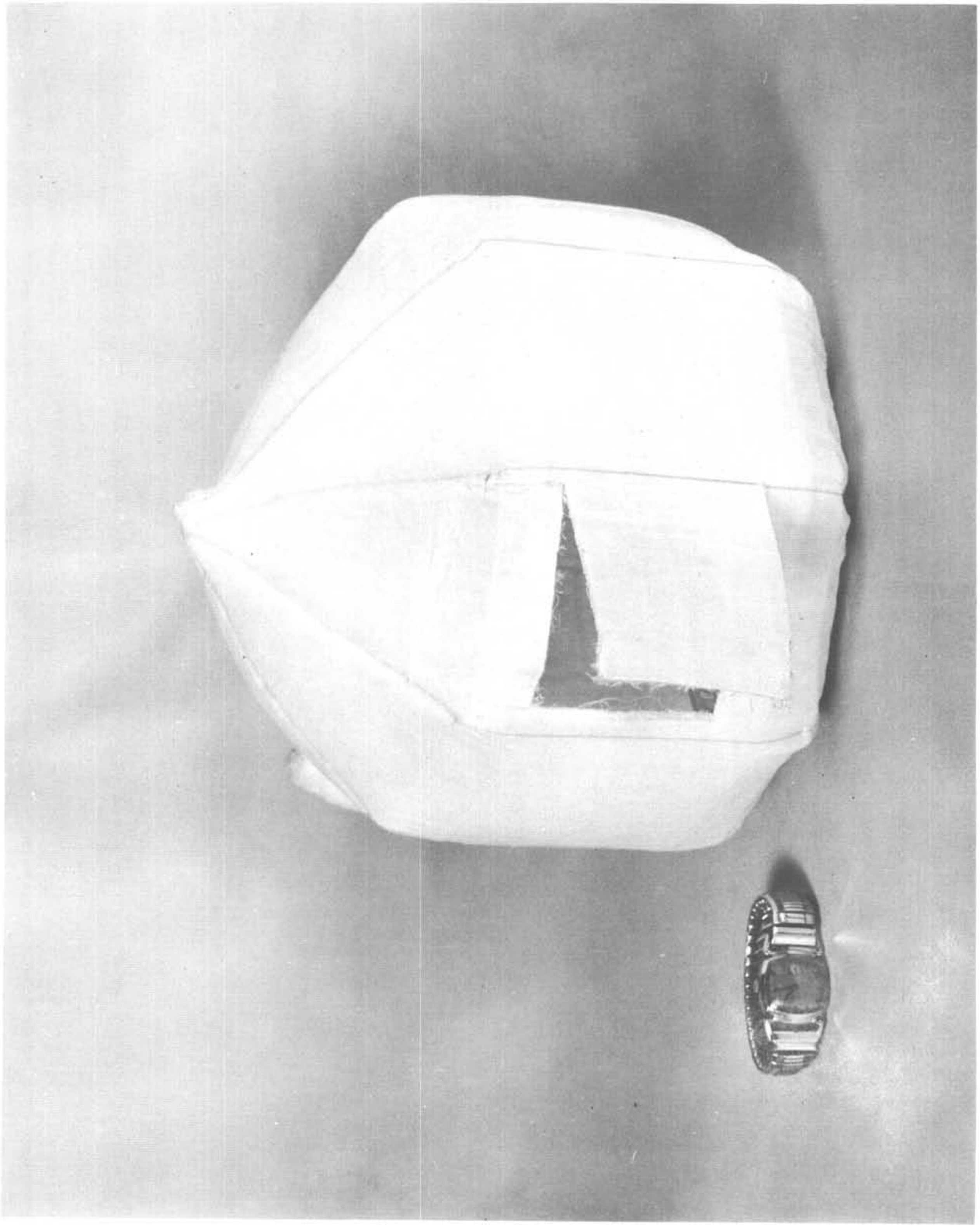

FIGURE 7 - NYLON SHELTER MODEL, 1/10 SCALE VAPOR CURED EPOXY

FIGURE 8 - GELATIN CURED 3 FT DIAMETER CYLINDER

FIGURE 9 - URETHANE CURED 7 FT DIAMETER SPACE SHELTER

FIGURE 11 - DEPLOYED AND RIGIDIZED 13 x 15 FT AEROSPACE MAINTENANCE DOCK

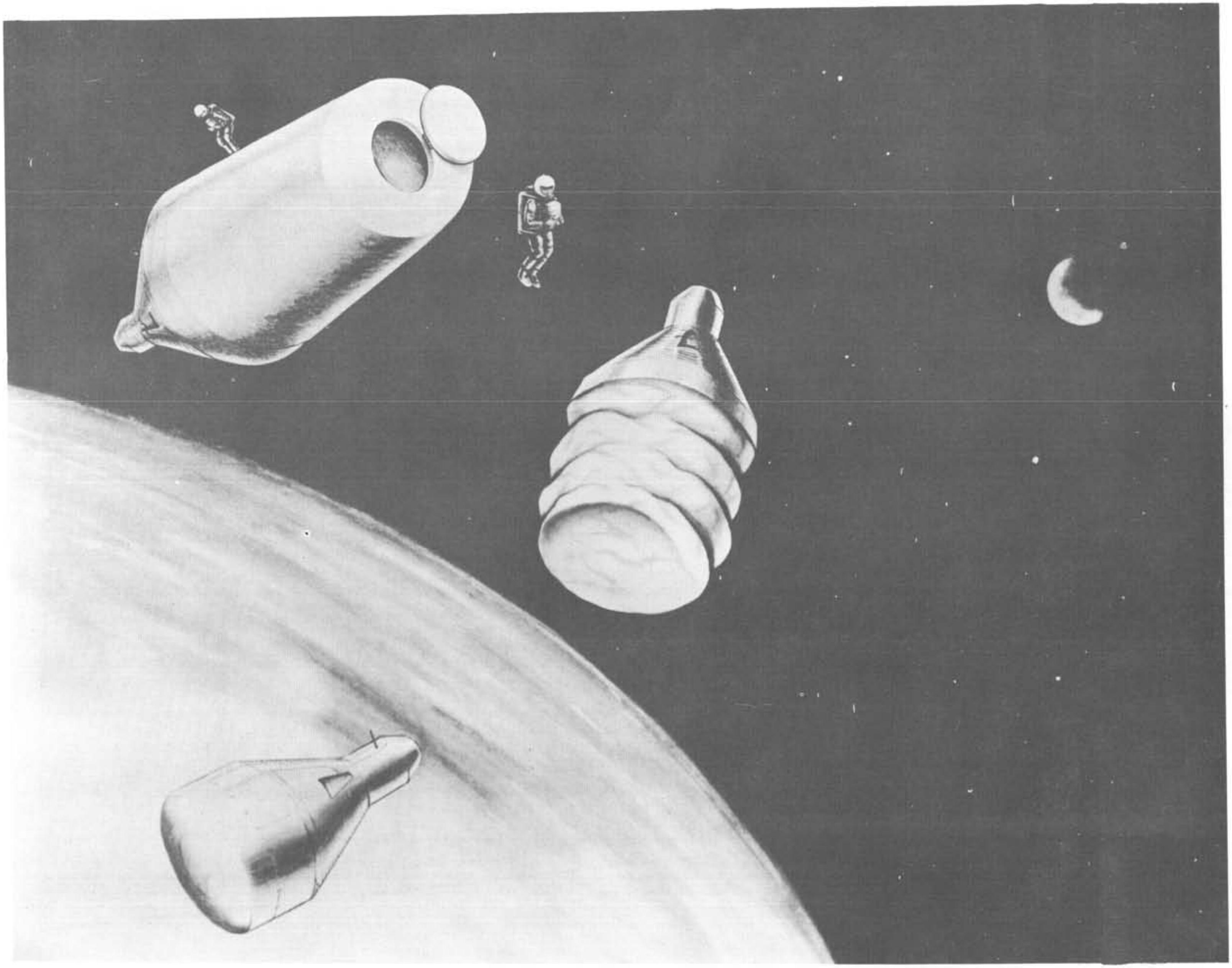

FIGURE 12 - ARTISTS CONCEPT OF AN EXPANDABLE CYLINDRICAL SPACE STRUCTURE

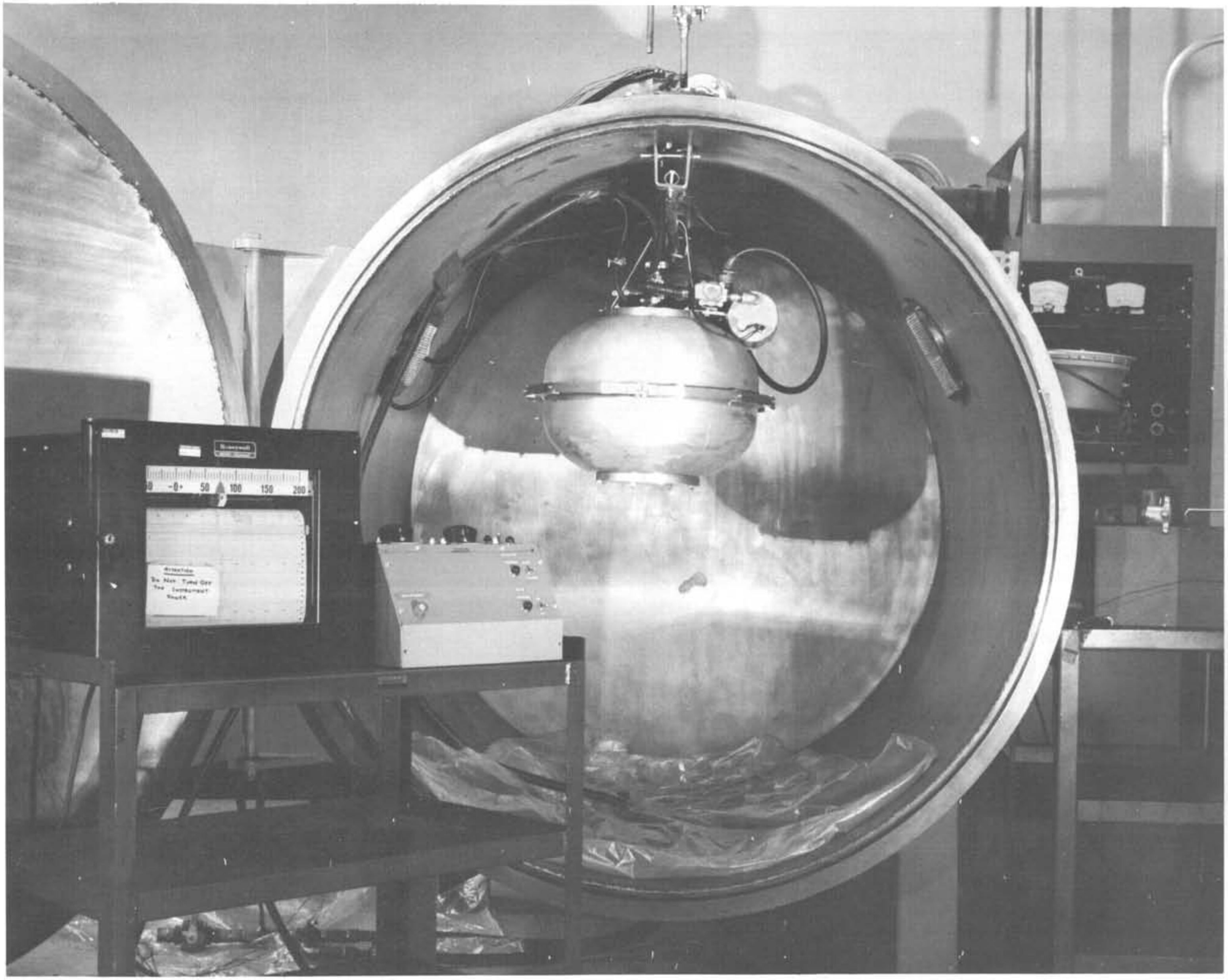

FIGURE 13 - MODEL SIZE CYLINDRICAL SPACE STRUCTURE WITHIN THE CANISTER

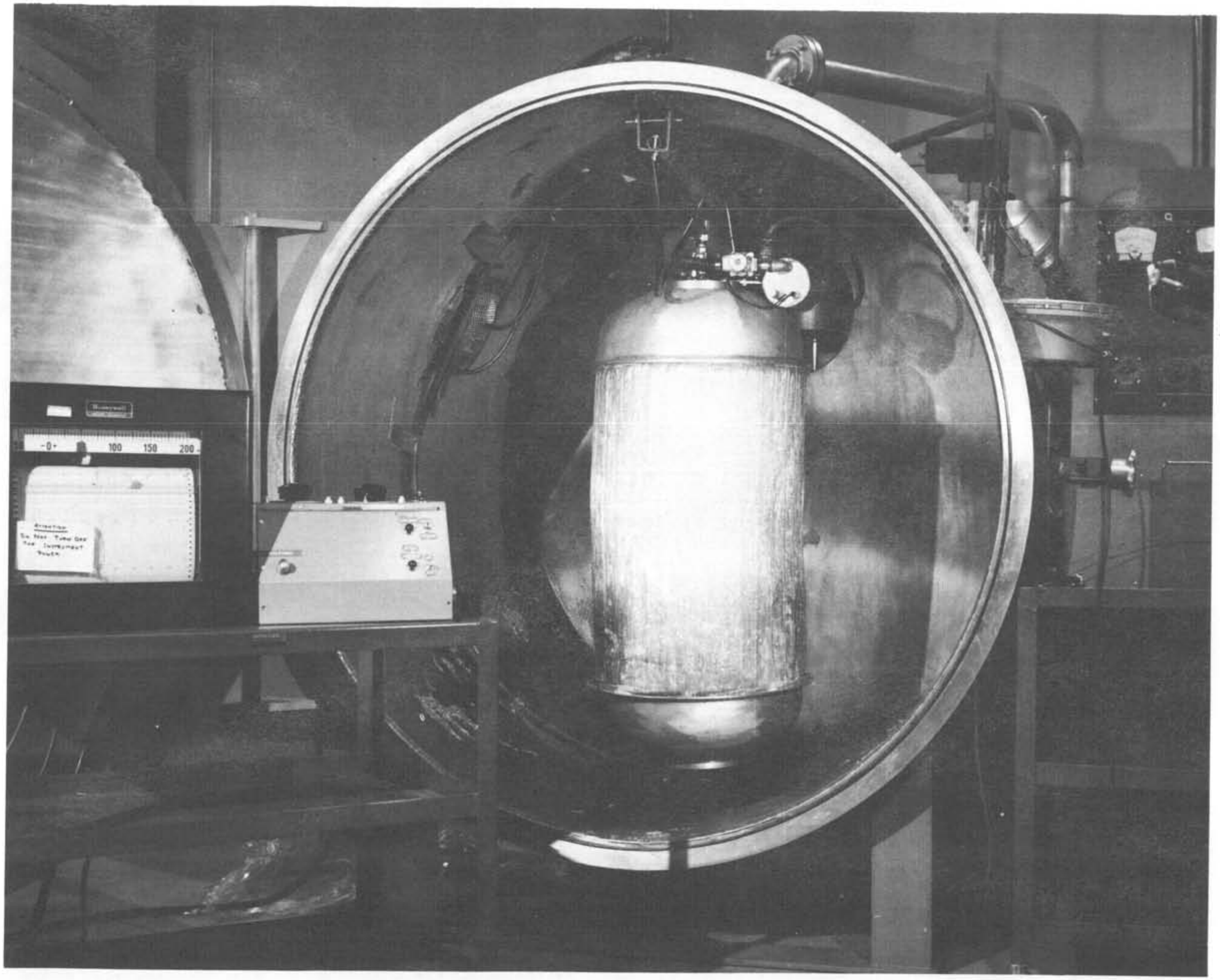

FIGURE 14 - DEPLOYED 1/6 SIZE CYLINDRICAL SPACE STRUCTURE

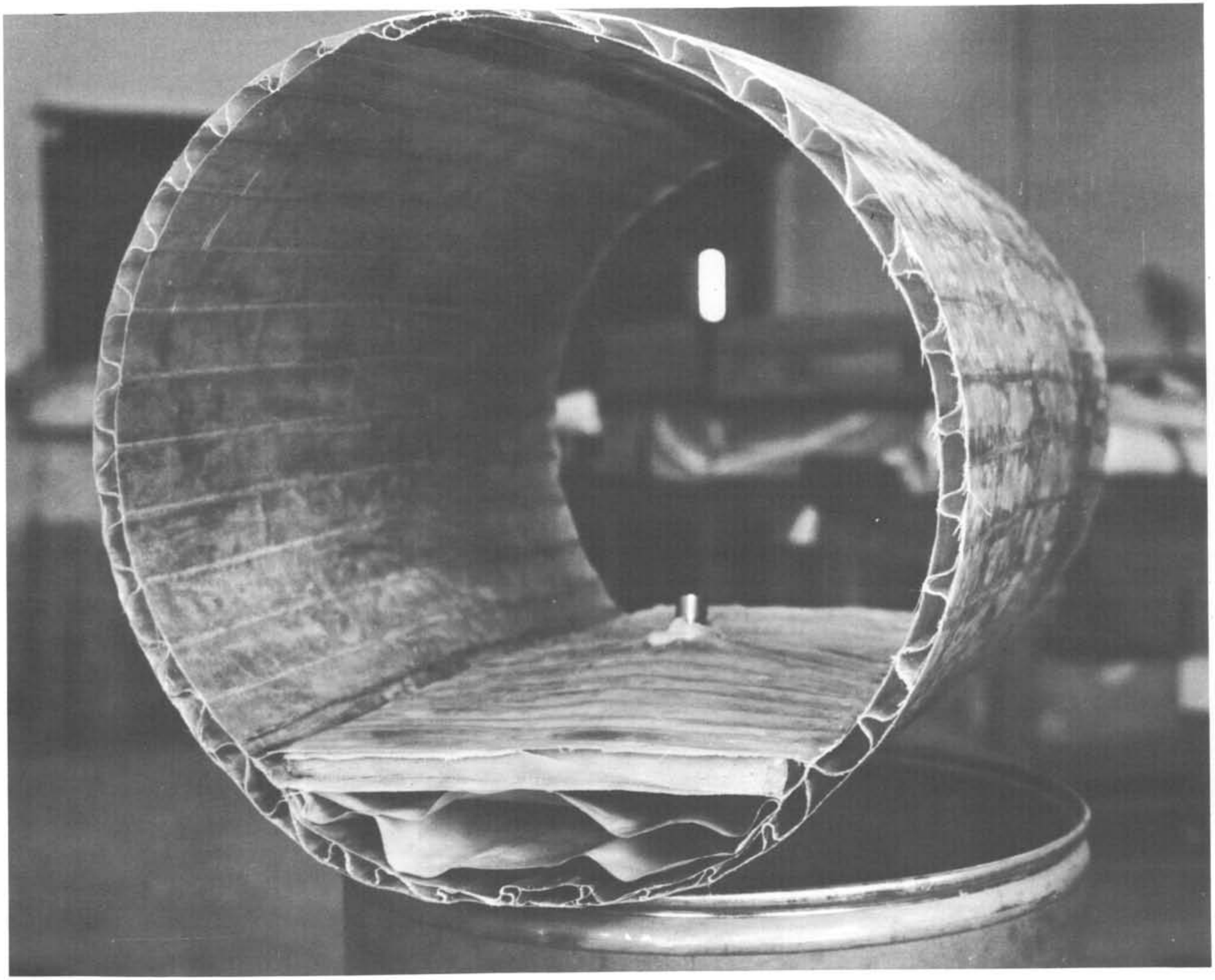

FIGURE 15 - CYLINDER WALLS IN 1/6 SIZE CYLINDRICAL SPACE STRUCTURE